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Biogas utilization: Experimental investigation on biogas flameless combustion in lab-scale furnace

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ABSTRACT

Biogas generated in the anaerobic digestion of biomass and organic wastes by micro-organisms can be applied for heating, transportation and power generation as a renewable energy source. However, low calorific value (LCV) of biogas is one the most important bottlenecks of biogas conversion into electrical or thermal energy. Indeed, the presence of corrosive gases such as H_2S and water vapor in biogas components makes some dilemmas in biogas purification and utilization. In order to obtain the efficient biogas utilization method, different biogas resources, physical and chemical properties of biogas and biogas combustion characteristics should be considered. In this paper biogas was utilized in lab-scale flameless combustion furnace and the performance of flameless combustion chamber fueled by biogas has been presented. Results demonstrated that flameless combustion is one of the best feasible strategies for biogas utilization. Uniformity of temperature in the flameless furnace increases the durability of refractory and related equipment. Simplicity of the flameless burner, pollutant formation reduction and fuel consumption decreases are the main causes of biogas flameless combustion supremacy.

1. Introduction

Fossil fuel depletion and the increasing rate of pollutant formation have encouraged scientists to find environmentally friendly alternative fuels to guarantee the secure energy provision and people health. Besides, clean development strategies have conducted combustion technologies to fuel consumption reduction and low pollutant formation to attain sustainable purposes. Experimental investigations confirm that biomass has shown its compatibility with current combustion systems and biomass has promised to be applied as an alternative fuel to solve the future fossil fuel shortage. Biogas utilization and production technology offered in biomass category to meet a portion of energy demand of the world. Therefore, biogas users must have comprehensive knowledge of the available technological options for biogas utilization. Indeed, general knowledge of the physical and chemical properties and combustion characteristics of the biogas is needed to have efficient combustion. Also, the required systems for biogas storage, transportation and clean up comparison are selected based on all of this information [1,2]. Totally, the best system selection for biogas conversion into thermal energy for transportation, gas turbine, heating, lighting and small-scale power generation is the main target of biogas production and utilization steps [3]. Among various environmentally friendly combustion technologies emerged in recent decade, flameless combustion has been attracted more attentions due to its excellence such as fuel consumption reduction, stability of combustion, temperature uniformity and low pollutant formation [4]. Generally, preheating the diluted oxidizer over the self-ignition of the fuel is the main key of flameless combustion achievement [5]. Thermal and chemical structures of diluted biogas by nitrogen in counter-flow diffusion flames were investigated by Jahangirian et al. [6]. It was found that by biogas utilization the net emission of three greenhouse gases CO_2, CH_4 and N_2O decreased drastically in comparison with pure methane [6]. Performance evaluation of flameless combustion furnace fueled by natural gas and biogas was investigated by Colorado et al. [7]. It has been stated that flameless combustion technology has great capability to apply LCV fuels like biogas as a fuel [7]. Biogas flameless combustion has great capability to reduce pollutant constitution especially soot formation [8]. Since biogas purification is very expensive and its conventional combustion in industrial boilers is not feasible, flameless combustion as the best method for biogas utilization has been investigated in this paper.

1.1. Biogas main resources

The distinction point of biogas production system from other biofuels is its power point in collecting the organic waste materials and producing irrigation water and fertilizer simultaneously. Biogas production is not complicated process and unlike other alternative fuel forms does not have any geographical limitations [9]. Municipal solid waste (MSW), coal mining, rice paddies, rising main sewers, landfills and old waste deposits, anaerobic digestions,

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cattle ranching and agricultural products are the main sources of biogas in the world [10–18]. Moreover, the increasing rate of world population is the main cause of food industries and especially animal husbandry development and one of the most important sources of CH_4 in the world is animal husbandry [19]. It has been proven that more than 15% of global methane generation is related to CH_4 emission from ruminants and biogas capturing from livestock dung and energy generation from waste gases have become routine process in many countries [20]. The appropriate strategies in waste water recirculation can increase the possibility of biogas generation as a renewable fuel from these waste materials [21]. Around 90–95% of natural gas is methane, but in biogas the rate of methane depends on feedstock decreases to the values of 55–65%. Therefore, biogas is a low calorific value (LCV) gas or low grade natural gas. Generally, the collected biogas is purified and its impurities like water and sulfuric gases removed. The biogas purification method and combustion improvement strategies are designed based on composition of biogas. The general composition of biogas has been shown in Table 1 [22].

1.2. Biogas general characteristics

In ideal conditions 40–80% of biogas is constituted by CH_4 and at the standard pressure and temperature the lower heating value of CH_4 is about 34,300 kJ/m^3. Therefore, the lower heating value of biogas is approximately 13,720–27,440 kJ/m^3. However, in biogas heating value determination, the heating value of the whole components should be taken into consideration. It means that the heating value of non-combustible specious like CO_2 should be taken into account. Also, the noticeable effects of water vapor on lower heating value, air–fuel ratio, biogas flammability limits and flame temperature should not be neglected. The physical characteristics of biogas are usually modeled by CO_2 and CH_4 because more than 98% of biogas is a combination of these two gases. However, hydrogen sulfide (H_2S) and water vapor removal process are vital in biogas production process due to their crucial role in equipment corrosion especially burner and boiler in conventional combustion chambers. Chemical and physical characteristics of CH_4 and CO_2 as the main components of biogas have been presented in Table 2.

In order to achieve an effective biogas conventional combustion some pretreatments should be done in biogas production step. H_2S and water as biogas corrosive constituents and other useless components of biogas such as CO_2, N_2 and hydrocarbons should be removed to obtain better traditional combustion. A summary of biogas pretreatments for elimination of detrimental components are presented in Table 3 [23].

2. Biogas combustion

2.1. Biogas flame velocity and temperature

The velocity of flame plays crucial role in the burner design in conventional combustion. The rate of injected fuel and air to the burner should be matched to flame velocity to prevent blowing out the flame. Compared to the natural gas the biogas flame velocity decreases due to lower concentration of CH_4 in biogas. Therefore, in biogas conventional combustion the flow rates of air and fuel injected to the burner should be decreased to prevent flame blow out. The maximum velocity of the flame is occurred at the stoichiometric air to fuel ratio. The other important parameter in the performance of combustion systems is the flame temperature. The design of refractory, insulation and other heat recovery equipment of combustion systems are done based on the flame temperature of the fuel because the rates of heat transfer from combustion system and flame temperature of combustible mixture have a direct proportion. In traditional combustion condition the flame temperature of biogas is lower than natural gas due to presents of non-combustible components such as CO_2 and water vapor [24].

Table 1
Biogas general composition.

Biogas components	Typical analysis (% by volume)
Methane (CH_4)	55–65
Carbon dioxide (CO_2)	35–45
Hydrogen sulfide (H_2S)	0–1
Nitrogen (N_2)	0–3
Hydrogen (H_2)	0–1
Oxygen (O_2)	0–2
Ammonia (NH_3)	0–1

2.2. Biogas flameless combustion

Biogas direct combustion in the furnace named conventional combustion is the simplest method of biogas utilization. Since biogas characteristics compared to natural gas are totally different, some substantial modification in control system, fuel delivery system, burner and orifice should be done to upgrade the combustion system for biogas utilization. In the other hand, low calorific value of biogas is the great obstacle for biogas conventional combustion. Furthermore, biogas upgrading for CO_2 elimination from biogas components is very expensive process. All of aforementioned disadvantages can be removed by biogas flameless combustion because flameless method can work well with extremely small LCV fuels and CO_2 removal from biogases is not necessary because CO_2 is applied to dilute the oxidizer. Indeed, ceramic which is applied in the burner and refractory of flameless furnace is a resistant in front of corrosive components of biogas like water vapor and H_2S. In natural gas flameless combustion the reactants are natural gas and highly diluted air. Also, the inside temperature of the flameless furnace should be above the self-ignition temperature of the natural gas. In these conditions traditional flame is not stable and the flame lifts. In the other word, due to low oxygen concentration and high Reynolds number for oxidizer, the flame structure is changed and the conventional flame is disappeared [25]. In order to achieve flameless combustion, combustion system should be run in traditional mode at the first step. This preheating step prevents reaction from quenching and increases the flameless chamber temperature above the self-ignition temperature of the fuels (normally more than 1000 K). When the temperature inside the furnace raises adequately, the reactance jet velocity increased, therefore the flame is disappeared and the furnace average temperature declines, this zone also is named as instability zone. Visible and audible flame is eliminated and the reaction region spreads to the downstream zone of the chamber. Therefore, temperature distribution is uniform along the flameless chamber, hot spots are eliminated and thermal NO_x formation suppressed [26].

3. Methodology

3.1. Experimental set up

Carbon steel pipe with 264 mm diameter and 600 mm length applied as the flameless furnace. An especial ceramic made by local factories used as refractory inside the chamber to maintain the inside temperature. The real diameter of the chamber is 150 mm after installation of refractory. Five holes have been set at the top of the chamber in specific distances from burner for K-type thermocouples installation. Fig. 1 shows the furnace before equipment installation and Fig. 2 is a picture of the combustion system during installation.

Table 2
Physical and chemical properties of CO_2 and CH_4.

Physical and chemical properties[a]	CO_2	CH_4
Specific gravity, air = 1[b]	1.52	0.554
Specific volume	0.55 m^3/kg	1.51 m^3/kg
Heat capacity, C_p@101 kPa	858 J/kg k	2261 J/kg k
C_p/C_v	1.303	1.307
Limit of inflammability	_	5–15% by volume
Stoichiometry in air	_	0.0947 by volume 0.0581 in mass

[a] Pure gas properties are given at atmospheric pressure and 25 °C.
[b] Air at 101 kPa, 15.6 °C.

Table 3
Biogas pretreatments for elimination of detrimental components.

Components	Main process	Process
H_2S and CO_2	Adsorption	Molecular sieves
		Activated carbon
	Membrane Separation	Hollow fiber membrane
	Absorption	Organic solvents
		Alkanolamines
		Alkaline salt solution
Water vapor	Adsorption	Silica gel
		Molecular sieves
		Alumina
	Absorption	Selexol
		Ethylene glycol
	Refrigerating	Chilling to 2 °C
Hydrocarbons	Adsorption	Activated carbon
	Absorption	Ethylene glycol
		Lean oil absorption
		Selexol
	Combination	Refrigeration with ethylene glycol plus activated carbon adsorption

The required air for combustion provided by a fan and the fresh air preheated by furnace exhaust gases in a heat exchanger. Although, using regenerative or recuperative heat exchangers have been mentioned as the best equipment for heat recovery in flameless combustion method, they are very expensive [27]. In our lab-scale investigation an auxiliary electrical heater was used to keep the air temperature over the auto-ignition temperature of biogas. Gas and air flow rate controllers, gas analyzer, suitable control valves, digital temperature indicator, biogas and CH_4 capsules are the other components applied in this project. Fig. 3 illustrates the schematic of project experimental set up.

3.2. Burner

One of the most important advantages of flameless combustion systems is the simplicity of the burner. A blind flange with nine holes plays the burner's role in this experiment. The central hole has been contrived for biogas injection and others have been dedicated for preheated air injection. At the first step the burner was operated conventionally fueled by CH_4 in order to heat up the walls of the chamber over the biogas self-ignition temperature and then the system switched to flameless combustion mode. Fig. 4 demonstrates the configuration of the burner.

4. Implementation of the flameless combustion process

Initially, the combustion chamber operated conventionally fueled by CH_4 to heat up the chamber. During traditional mode, the exhaust gases are evacuated through valve 4 and heat exchanger and auxiliary heater were not used, therefore compared to the flameless mode the efficiency of the system is lower in conventional combustion. Table 4 illustrates the situation of various control valves which were mentioned in Fig. 1 in different steps.

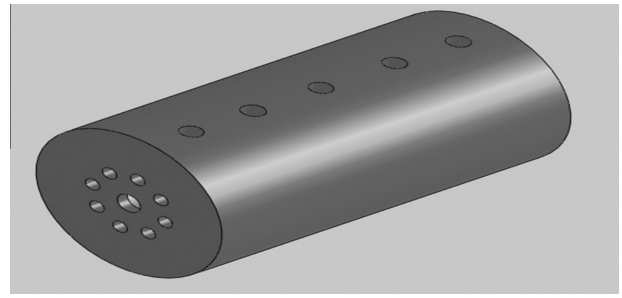

Fig. 1. The shape of the furnace before equipment installation.

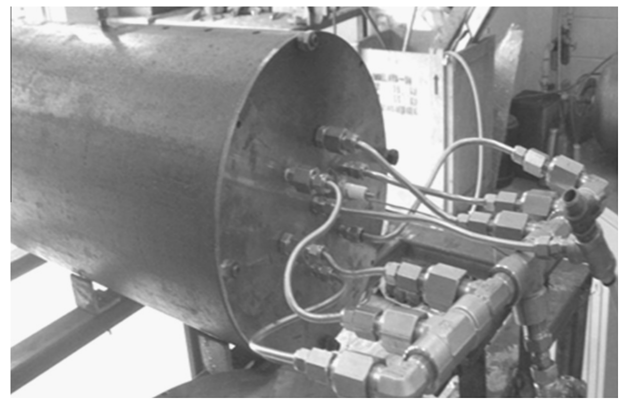

Fig. 2. Combustion system during installation.

Transient from conventional flame to flameless combustion implemented when the furnace heat up adequately and the temperature inside the chamber was higher than 1300 K. In this step CH_4 injection was stopped. Also, exhaust gases was led to the heat exchanger. Finally, biogas was conducted to the combustion system immediately and auxiliary heater was used when the temperature inside the chamber decreased. During biogas flameless mode total flue gas flow rate was extracted through the heat exchanger. A process at 1050 K was simulated and the average temperature of the walls was held over 1070 K to ensure the auto-ignition of biogas during the experiment. The air combustion was preheated at 950 K during the operation in flameless mode. During the experiment some parameters were measured to evaluate the performance of the combustion system. Temperature of the horizontal axes at the middle of the furnace recorded permanently by temperature indicators connected to the K-type thermocouple. Also, the inner chamber walls temperature was recorded frequently. Indeed, the history of air, biogas and CH_4 flow rates and exhaust gases during conventional CH_4 combustion and biogas flameless combustion were recorded. The flow rates were measured with mass flow meters. Also, pressures and temperatures were measured by different gages for each flow. Furthermore, a type of gas analyzer was applied to analysis the species of different pollutants in exhaust gases pipe.

5. Results and discussion

5.1. Temperature profile

The recorded temperature profiles along the central axis of the furnace during CH_4 conventional combustion and biogas flameless combustion have been illustrated in Fig. 5.

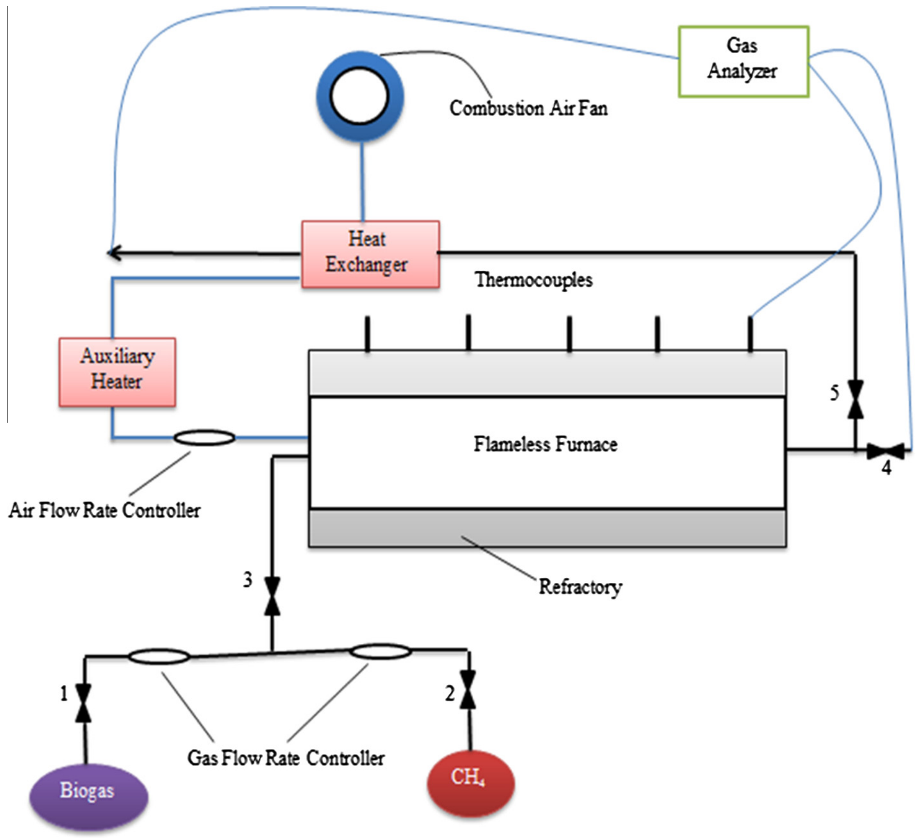

Fig. 3. Experimental set up.

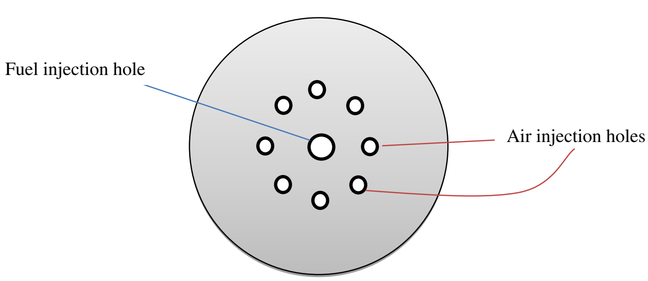

Fig. 4. The configuration of the burner.

Table 4
Situation of various control valves in different steps.

Control valve	Step 1	Step 2	Step3
1	Close	Close	Open
2	Open	Close	Close
3	Open	Open	Open
4	Open	Close	Close
5	Close	Open	Open

The temperature of the biogas flameless mode is lower than CH_4 conventional combustion in whole of the furnace. However, in conventional combustion, temperature fluctuated from one point to the other point of the chamber and hot spots can be constituted easily. In flameless combustion the temperature inside the furnace was uniform averagely 1050 K. The increased amount of CO_2 flowing in the combustion furnace cools down the combustion reactions lowering the chamber's temperature. Also, CO_2 has superior cooling effects due to its high heat capacity (C_p) at high temperatures and its enhanced radiation characteristics allow it to absorb more radiation from the reaction zone. These circumstances conduct the system to a temperature reduction of the chamber walls. These results are in agreement with the other experiments conducted by Szegö et al. [28] and Dally et al. [29]. Hosseini et al. [27] stipulated that flat temperature profile inside the furnace increases the durability of the industrial chamber's refractory; therefore hot spots elimination and the uniformity of the temperature inside the flameless chamber are the main advantages of the biogas flameless combustion. Conversely, in traditional combustion with methane a temperature peak was occurred near the burner. Yang et al. [30] defined a ratio for temperature uniformity inside the chambers to evaluate the temperature uniformity as follows:

$$R_u = \left(\sum \left(\frac{T - \bar{T}}{\bar{T}} \right)^2 \right)^{1/2}$$

where R_u is a temperature uniformity ratio, T(K) represents the measured temperature in every point of the furnace, and $\bar{T}$ is the average temperature. In flameless combustion R_u should tend to zero because the difference between T and $\bar{T}$ in every point of the furnace is very small. In order to asses R_u in this experiment all the recorded temperature of the horizontal axes at the middle of the furnace were employed and R_u was equal to 0.05. Reynolds number of the biogas central jet was around 20,500 and the preheated air stream velocity was held constant around 85 m/s, therefore the temperature uniformity regarding the biogas is a consequence of the turbulence circumstance and mixing patterns improvement. Indeed, the presence of CO_2 which is the main part of biogas enhances the rate of radiation and leads the system to a better distribution of the heat throughout the furnace.

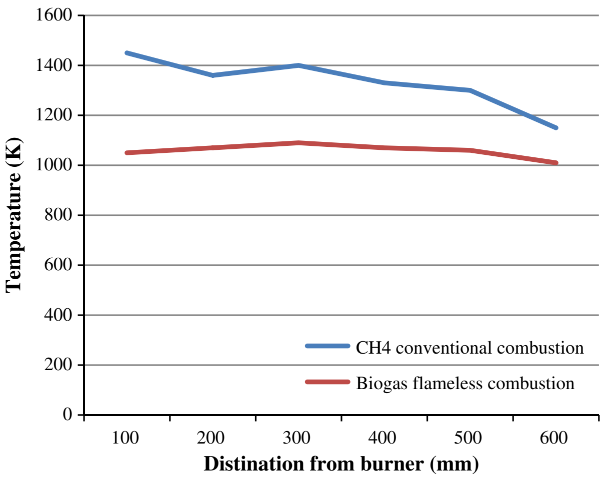

Fig. 5. The temperature profiles along the central axis of the furnace during CH_4 conventional combustion and biogas flameless combustion.

5.2. Various specious inside the chamber

Fig. 6 depicts volumetric concentration of oxygen and CO_2 along the second half part of central axis of flameless furnace fueled with biogas.

The distribution of oxygen along the second half of the flameless furnace was uniform. The oxygen concentration recorded around 7% for biogas flameless mode. The low oxygen concentration and the uniform temperature over the biogas auto-ignition temperature guaranteed the appropriate circumstances for the flameless combustion formation. Regarding the CO_2 formation in biogas flameless combustion, very high CO_2 concentration was recorded due to the additional amount of CO_2 in biogas composition. It is noteworthy, in pure CH_4 combustion with an excess of fresh air of 21%, the maximum CO_2 formation in the fumes recorded 10.8% whereas biogas conventional combustion with the same excess air, the CO_2 constitution in the fumes was measured around 22%. The uniform concentration of oxygen and dioxide carbon recorded along the flameless combustion furnace confirms an excellent mixing of the reactants with the products gases throughout the furnace due to very high Reynolds of injected preheated air. Hydroxyl radical (OH) formation in flameless combustion is very sensitive to the fluctuations of temperature [31]. Medwell et al.

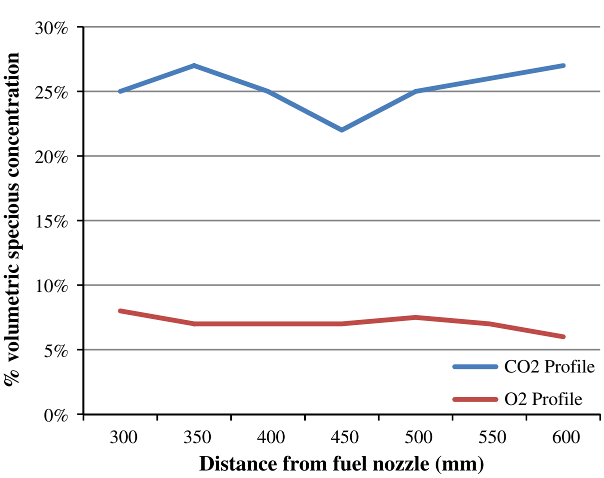

Fig. 6. Concentration of O_2 and CO_2 along the second half part of central axis of biogas flameless furnace.

[32] pointed out that hydroxyl radical (OH) concentration reduces when the volumetric oxygen concentration in the oxidizer decreases. Szegö et al. [28] stipulated that the CO emission in flameless regime is higher than traditional flame due to low concentration of OH radicals which control the CO conversion to CO_2. Fig. 7 shows monoxide carbon (CO) and Fig. 8 depicts CH_4 constitution profiles along the furnace during methane conventional combustion and biogas flameless combustion.

These figures indicate that the species patterns of the burner fueled with methane in conventional mode, and biogas flameless combustion. In methane traditional combustion mode the concentration of CO was recorded around 30 ppm, while CH_4 concentration was around 0.5%. This result indicates that the complete fuel combustion occurred in the zone close to the burner. On the other hand, in biogas flameless combustion regime a peak of CO and CH_4 was recorded at 300 mm from the burner. Then, when the distance from the fuel nozzle increases, the CO and CH_4 formation decrease gradually. These results confirm that the region of reactions is much longer in flameless combustion. In the other word, the combustion phenomena cover the whole length of the furnace. The complete oxidation of CO and CH_4 in flameless combustion mode is obtained due to the high velocity of reactants and turbulence condition, the high temperature of the preheated air above the biogas self-ignition temperature and the oxygen availability throughout the chamber.

5.3. Pollutant formation

The recorded results by gas analyzer confirm that in biogas flameless combustion regime pollutant formation decreased drastically in comparison with conventional combustion. Fig. 9 illustrates pollutant concentration in the exhaust section of the chamber in biogas flameless mode.

Pollutant concentration records indicate that flameless combustion is more prone to CO formation than traditional combustion due to the highly diluted circumstances of the flameless mode. It means that low concentration of oxygen reduces hydroxyl radicals (OH) formation which effect on conversion of monoxide carbon to dioxide carbon [33]. Indeed, NO_x formation is suppressed in flameless combustion. Based on Zeldivich formulation, some parameters such as very high temperature and hot spots constitution inside the combustion furnace, resident time and high amounts of oxygen in combustion phenomena plays crucial role in thermal NO_x formation [34]. According to Fig. 5, compared to the traditional combustion, the temperature inside the furnace is lower and uniform in flameless mode. Uniformity of the temperature inside the flameless chamber and consequently avoiding hot spots constitution, high velocity of reactants and low oxygen concentration in this experiment are the main causes of low NO_x formation [35–37]. In the other word, thermal NO_x which is mentioned as the main regime of NO_x formation is eliminated in flameless combustion and other inconspicuous NO_x formation regimes such as prompt NO_x and N_2O intermediate NO_x remained [38–40]. Fig. 10 shows the trend of NO_x formation in biogas flameless combustion by increasing the rate of temperature and oxidizer. It can be concluded that more access air and increases preheated air temperature augment the rate of NO_x formation in biogas flameless regime.

6. Energy assessment

In order to calculate the energy balance of the biogas flameless combustion all of the thermal parameters such as the rate of energy enters into the furnace with biogas, and the fresh air that enters into the chamber before preheating and the thermal energy input by heater were taken into consideration. In biogas flameless

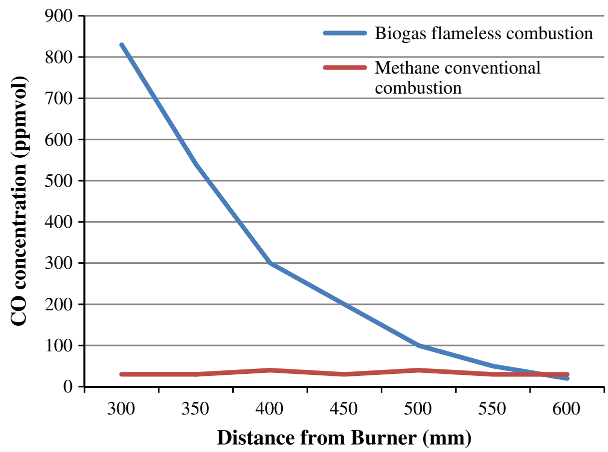

Fig. 7. CO formation profiles along the furnace.

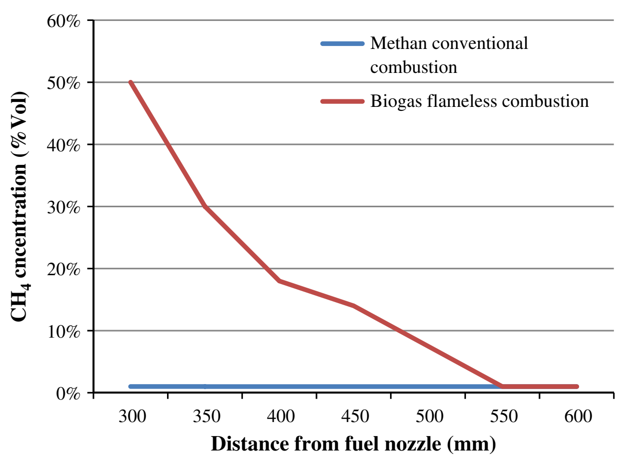

Fig. 8. CH_4 constitution profiles along the furnace.

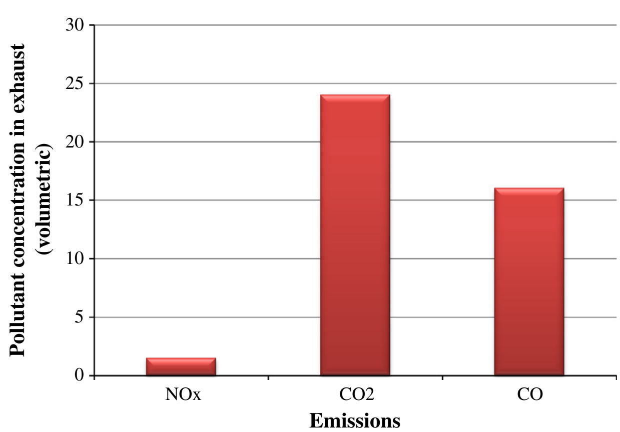

Fig. 9. Pollutant concentration in biogas flameless mode.

operation and methane traditional combustion the rate of input thermal energy was held approximately 8 kW. Indeed, thermal power of auxiliary heater for biogas flameless combustion which was applied temporary was recorded 0.3 kW. Also, after the temperature measurement of the furnace walls and considering convention and radiation heat transfer, the heat lost from combustion chamber walls was calculated 1 kW and 1.45 kW for biogas flameless combustion and methane conventional combustion respectively in steady state conditions or 2 h after operation

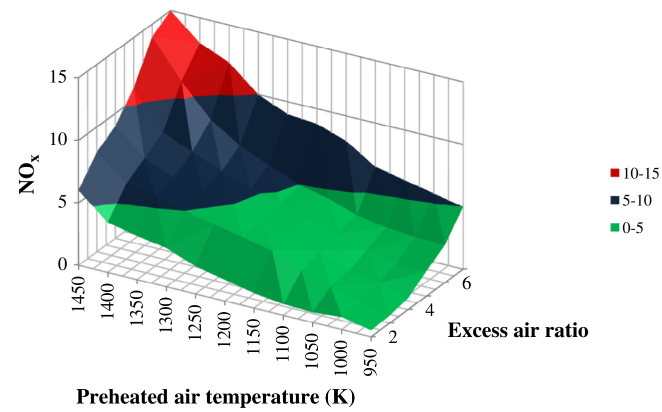

Fig. 10. NO_x formation in biogas flameless combustion.

Table 5
Energy assessment of the furnace fueled by methane in traditional mode and biogas in flameless regime.

Energy balance		Methane traditional combustion	Biogas flameless combustion
Input (kW)	Energy of fuel and combustion air	8	8
	Heater	0	0.3
Heat loss (kW)	Energy losses through the furnace wall	1.54	1.2
	The output energy through the emissions	3.9	2.7
Output (kW)	Input-heat loss	2.56	4.4
	Efficiency (%)	32%	53%

based on the outer temperature of the walls and applying approach for radiation and convection heat transfer from walls. The efficiency of biogas flameless combustion was calculated 53% and in conventional methane combustion the efficiency of the chamber was around 32%. This low efficiency was occurred because in traditional mode all of the combustion products were conducted through valve 4 to exhaust instead of energy recovery. Table 5 demonstrates energy assessment of the furnace fueled by methane in traditional mode and biogas in flameless regime.

In biogas flameless combustion when the temperature of the exhaust part of the chamber was recorded around 1050 and half of the total emissions were conducted to the chimney, the heat loss from emissions was 32% of total input energy. Compared to the methane flameless combustion, biogas heat loss from chimney is higher which has been attributed to the higher radiation heat transfer from high amounts of CO_2 particles [7]. However, for methane traditional combustion the heat loss from exhausted products in the chimney was about 48% of the energy input. To understand the importance of heat recovery in traditional combustion, heat exchanger was used during CH_4 traditional combustion. It means that the control valve 4 was closed and valve 5 opened. The efficiency of the chamber augmented to 44% however NO_x formation increased drastically. In biogas flameless mode more than 82% of exhaust gases energy was recovered in heat exchanger to increase the temperature of fresh air and around 18% of this energy lost.

7. Conclusion

Although, biogas resources can be found easily in every point of the world in biomass category, biogas utilization has been

encountered some dilemma problems. Presents of corrosive gases such as water vapor and H_2S in biogas combination, high costs of biogas purification and low colorific value of biogas are the main obstacles for development of biogas utilization. These corrosive materials can damage the equipment during biogas purification or direct combustion. Biogas can be applied directly in flameless combustion without substantial changes. Under the biogas flameless combustion the performance of flameless chamber remained constant. Indeed, CO and NO_x formation were recorded very low. The efficiency of biogas flameless combustion is higher than traditional mode due to heat recovery of exhaust gases in heat exchanger. Heat loss from the emissions in biogas flameless combustion was recorded lower than traditional mode due to heat recovery. Also, the high concentration of CO_2 in biogas flameless combustion products causes higher heat capacity; better radiation heat transfer and higher absorption capacity which improve the performance of heat exchanger. The profile of CH_4 and CO formation inside the chamber indicates that in biogas flameless combustion the reaction zone is distributed along the whole length of the furnace. Therefore, the temperature inside the furnace is uniform in biogas flameless mode and hot spots are eliminated and thermal NO_x are suppressed. Indeed, experimental results confirmed that increasing the temperature of preheated air and access air raise the rate of NO_x constitution. Also, increasing the durability of equipment especially burner and refractory is the main advantages of temperature uniformity inside the combustion chamber. Fuel consumption reduction, low noise and pollutant formation are the other advantages of biogas flameless combustion.

References

[1] Hosseini Seyed Ehsan, Wahid Mazlan Abdul. Feasibility study of biogas production and utilization as a source of renewable energy in Malaysia. Renew Sustain Energy Rev 2013;19:454–62.
[2] Hosseini Seyed Ehsan, Wahid Mazlan Abdul. Necessity of biodiesel utilization as a source of renewable energy in Malaysia. Renew Sustain Energy Rev 2012;16:5732–40.
[3] Chen Sheng, Zheng Chuguang. Counterflow diffusion flame of hydrogen-enriched biogas under MILD oxy-fuel condition. Int J Hydrogen Energy 2011;36(23):15403–13.
[4] Cavaliere Antonio, de Joannon Mara. Mild combustion. Prog Energy Combust Sci 2004;30(4):329–66.
[5] Dally BB, Riesmeier E, Peters N. Effect of fuel mixture on moderate and intense low oxygen dilution combustion. Combust Flame 2004;137(4):418–31.
[6] Jahangirian Saeed, Engeda Abraham, Wichman Indrek S. Thermal and chemical structure of biogas counterflow diffusion flames. Energy Fuels 2009;23(11):5312–21.
[7] Colorado AF, Herrera BA, Amell AA. Performance of a flameless combustion furnace using biogas and natural gas. Bioresour Technol 2010;101(7):2443–9.
[8] Effuggi Alessandro, Gelosa Davino, Derudi Marco, Rota Renato. Mild combustion of methane-derived fuel mixtures: natural gas and biogas. Combust Sci Technol 2008;180(3):481–93.
[9] Taleghani G, Shabani Kia A. Technical–economical analysis of the Saveh biogas power plant. Renew Energy 2005;30(3):441–6.
[10] Rasi S, Läntelä J, Rintala J. Trace compounds affecting biogas energy utilisation-a review. Energy Convers Manage 2011;52(12):3369–75.
[11] Lastella G, Testa C, Cornacchia G, Notornicola M, Voltasio F, Sharma Vinod Kumar. Anaerobic digestion of semi-solid organic waste: biogas production and its purification. Energy Convers Manage 2002;43(1):63–75.
[12] Machado, Sandro L, Carvalho Miriam F, Gourc Jean-Pierre, Vilar Orencio M, do Nascimento Julio CF. Methane generation in tropical landfills: simplified methods and field results. Waste Manage vol. 29, 1. p. 153–61.
[13] Dongkun Luo, Youjin Dai. Economic evaluation of coalbed methane production in China. Energy Policy 2009;37(10):3883–9.
[14] Fatih Demirbas M, Balat Mustafa, Balat Havva. Biowastes-to-biofuels. Energy Convers Manage 2011;52(4):1815–28.
[15] Demirbas Ayhan. Waste management, waste resource facilities and waste conversion processes. Energy Convers Manage 2011;52(2):1280–7.
[16] Albert Guisasola, Sharma Keshab R, Keller Jurg, Yuan Zhiguo. Development of a model for assessing methane formation in rising main sewers. Water Res 2009;43(11):2874–84.
[17] Cigdem Yangin-Gomec, Ozturk Izzet. Effect of maize silage addition on biomethane recovery from mesophilic co-digestion of chicken and cattle manure to suppress ammonia inhibition. Energy Convers Manage 2013;71:92–100.
[18] Yang Shang-Shyng, Liu Chung-Ming, Lai Chao-Ming, Liu Yen-Lan. Estimation of methane and nitrous oxide emission from paddy fields and uplands during 1990–2000 in Taiwan. Chemosphere 2003;52(8):1295–305.
[19] Nusbaum Neil J. Dairy Livestock methane remediation and global warming. J Commun Health 2010;35(5):500–2.
[20] Astals S, Ariso M, Galí A, Mata-Alvarez J. Co-digestion of pig manure and glycerine: experimental and modelling study. J Environ Manage 2011;92(4):1091–6.
[21] Takahashi J. Some prophylactic options to mitigate methane emission from animal agriculture in Japan. Asian – Aust J Anim Sci 2011;24:285–94.
[22] Balat M, Balat H. Biogas as a renewable energy source—a review. Energy Sources, Part A 2009;31(14):1280–93.
[23] Walsh JL, Ross CC, Smith MS, Harper SR. Utilization of biogas. Biomass 1989;20(3):277–90.
[24] Dai Wanneng, Qin Chaokui, Chen Zhiguang, Tong Chao, Liu Pengjun. Experimental studies of flame stability limits of biogas flame. Energy Convers Manage; 2012.
[25] Dally Bassam B, Karpetis AN, Barlow RS. Structure of turbulent non-premixed jet flames in a diluted hot coflow. Proc Combust Inst 2002;29(1):1147–54.
[26] Hosseini Seyed Ehsan, Wahid Mazlan Abdul, Ali Abuelnuor Abuelnuor Abdeen. High temperature air combustion: sustainable technology to low NO_x formation. Int Rev Mech Eng 2012;6(5):947–53.
[27] Hosseini Seyed Ehsan, Wahid MA, Ali Abuelnuor Abuelnuor Abdeen. Pollutant reduction and energy saving in industrial sectors by applying high temperature air combustion method. Int Rev Mech Eng 2012;6(7):1667–72.
[28] Szegö GG, Dally BB, Nathan GJ. Operational characteristics of a parallel jet MILD combustion burner system. Combust Flame 2008;156:429–38.
[29] Dally BB, Riesmeier E, Peters N. Effect of fuel mixture on moderate and intense low oxygen dilution combustion. Combust Flame 2004;137:418–31.
[30] Yang Weihong, Blasiak Wlodzimierz. CFD as applied to high temperature air combustion in industries furnaces. IRFR Combust J November; 2006.
[31] Aminian J, Galletti C, Shahhosseini S, Tognotti L. Key modeling issues in prediction of minor species in diluted-preheated combustion conditions. Appl Therm Eng 2011;31(16):3287–300.
[32] Medwell PR, Kalt PAM, Dally BB. Imaging of diluted turbulent ethylene flames stabilized on a jet in hot coflow (JHC) burner. Combust Flame 2008;152:100–13.
[33] Medwell PR, Kalt PAM, Dally BB. Simultaneous imaging of OH, formaldehyde, and temperature of turbulent nonpremixed jet flames in a heated and diluted coflow. Combust Flame 2007;148:48–61.
[34] Bowman Craig T. Kinetics of pollutant formation and destruction in combustion. Prog Energy Combust Sci 1975;1(1):33–45.
[35] Choi Gyung-Min, Katsuki Masashi. Advanced low NO_x combustion using highly preheated air. Energy Convers Manage 2001;42(5):639–52.
[36] Flamme Michael. Low NO_x combustion technologies for high temperature applications. Energy Convers Manage 2001;42(15):1919–35.
[37] Seepana Sivaji, Jayanti Sreenivas. Flame structure and NO generation in oxy-fuel combustion at high pressures. Energy Convers Manage 2009;50(4):1116–23.
[38] Hosseini Seyed Ehsan, Salehirad Saber, Wahid MA, Sies Mohsin Mohd, Saat Aminuddin. Effect of diluted and preheated oxidizer on the emission of methane flameless combustion. In AIP Conf Proc 2012;1440:1309.
[39] Bedoya Iván D et al. Experimental study of biogas combustion in an HCCI engine for power generation with high indicated efficiency and ultra-low NO_x emissions. Energy Convers Manage 2012;53(1):154–62.
[40] Galletti C, Parente A, Derudi M, Rota R, Tognotti L. Numerical and experimental analysis of NO emissions from a lab-scale burner fed with hydrogen-enriched fuels and operating in MILD combustion. Int J Hydrogen Energy 2009;34(19):8339–51.